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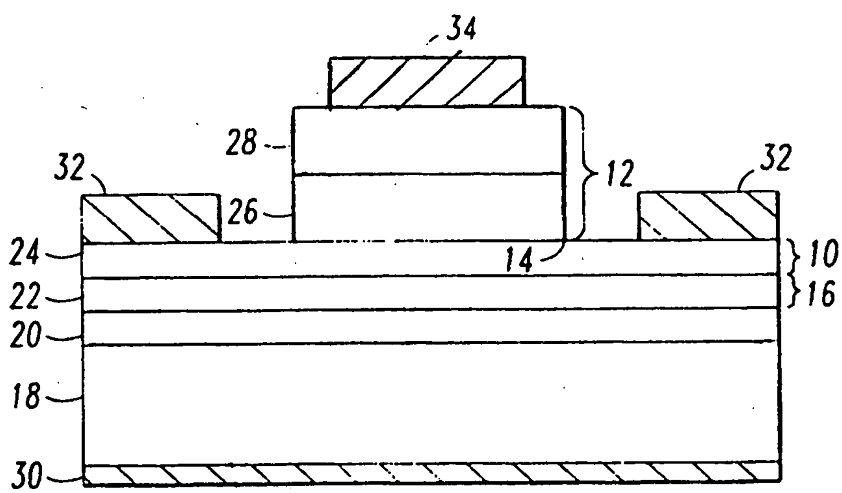
(54) Title: ALUMINIUM GALLIUM NITRIDE (ALGAN) BASED HETEROJUNCTION BIPOLAR TRANSISTOR

(57) Abstract

A heat tolerant, frequency responsive transistor for use in the microwave region includes a collector region (16), a base region (10) overlying the collector region, and an emitter region (12) including an AlGaN layer overlying at least part of said base region, forming a heterojunction (14) between said base region (10) and said emitter region (12). The emitter region may include two layers (26, 28). The HBT may be mounted on a SiC or sapphire substrate (18). The HBT may include a buffer layer (20) between the substrate (18) and the collector region (16).



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ALUMINIUM GALLIUM NITRIDE (ALGAN) BASED HETEROJUNCTION BIPOLAR TRANSISTOR

BACKGROUND OF THE INVENTION

Field of the Invention

The present invention is directed to heterojunction bipolar transistors (HBTs). More specifically, the present invention relates to HBTs for use as high power microwave amplifiers in S-X bands (3-12 GHz).

Description of the Related Art

The HBT concept is well known and has been successfully applied to several material systems e.g. $Al_xGA_{1-x}As/GaAs$, $Si_{1-x}Ge_x$ etc. Generally, the HBTs have been made on GaAs or Si substrates and suffer from three primary material limitations: (1) low electric breakdown field, (2) low saturated drift velocity of electrons, and (3) low thermal conductivity. All of these factors limit the power output of the device at a given frequency and the maximum frequency of operation.

Currently, silicon bipolar devices are being used in the UHF to S-Band frequency range while $Al_xGA_{1-x}As/GaAs$ HBTs are typically used at X-Band. $Si_{1-x}Ge_x$ HBTs are expected to outperform silicon bipolar transistors at S-band, with the possibility of operation to X-Band.

In the X-band, the $Al_xGA_{1-x}As/GaAs$ HBTs produce 3-4 W/mm of RF power at 10GHz and at room temperature. In addition, both Si and GaAs HBTs are capable of working at a junction temperature of 150°C.

U.S. Patent No 4,985,742 to Pankove discloses a transistor in which an n-type gallium nitride layer and a p-type silicon carbide layer from a heterojunction. The n-type gallium nitride layer serves as the emitter, the p-type silicon carbide layer serves as the base and a n-type silicon carbide layer, formed beneath the p-type silicon carbide layer serves as the collector. As disclosed in the related articles, "New Transistors take the Heat", Machine Design, August 10, 1995 p. 36 and Pankove et al., "High-Temperature GaN/SiC Heterojunction Bipolar Transistor with High Gain", Dec. 1994 IEEE, pp. 15.6.1 - 15.6.4, such a device can operate at high temperatures (up to 500°C) and have high current gains (greater than 10^5 at room temperature and around 100 at 500°C)

However, the need still exists for high power transistors for use in the microwave region, especially one having improved frequency response at around 3-12 GHz. The HBT structure disclosed by Pankove does not address microwave applications and is not designed for operation at high frequencies.

SUMMARY OF THE INVENTION

It is therefore an object of the present invention to provide a heat tolerant, frequency responsive transistor for use in the microwave region. It is a further object of the present invention to provide a transistor for practical use in the S-X band (3-12 GHz).

These and other objects of the present invention may be achieved by providing an HBT which includes a collector region, a base region overlying the collector region, and an emitter region including an AlGaN layer overlying at least part of the base region, forming a heterojunction between the base region and the emitter region. The emitter region may

include two layers. The HBT may be mounted on a SiC or sapphire substrate. The HBT may include a buffer layer between the substrate and the collector region.

These and other objects of the present invention will become more readily apparent from detailed description given hereinafter. However, it should be understood that the detailed description and specific examples, while indicating the preferred embodiments of the invention, are given by way of illustration only, since various changes and modifications within the spirit and scope of the invention will become apparent to those skilled in the art from this detailed description.

Brief Description of the Drawings

The present invention will become more fully understood from the detailed description given hereinbelow and the accompanying drawings which are given by way of illustration only, and thus are not limited to the present invention and wherein:

Figure 1a illustrates the structure of an HBT of a first embodiment of the present invention;

Figure 1b illustrates the structure of an HBT of a second embodiment of the present invention;

Figure 1c illustrates the structure of an HBT of a third embodiment of the present invention;

Figure 1d illustrates the structure of an HBT of a fourth embodiment of the present invention; and

Figure 2 is a table showing the overall figure of merit for candidate devices.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

In constructing HBTs as shown, for example, in Figures 1a - 1d, a base 10 is doped higher than an emitter 12 to reduce the base resistance at the expense of current gain. As long as the current gain is higher than ten, it does not impact the power gain

or efficiency. Indeed, too high (e.g., over 100) a current gain reduces the common emitter breakdown voltage and causes oscillations. Thus, the main functional difference between the present invention and the Pankove HBT is that while Pankove's HBT is designed to have a current gain of 1 million at room temperature, the HBT of the present invention has a current gain of only 10-100, but improved high frequency response.

A heterojunction at a base-emitter junction 14 allows the base 10 to be doped heavily without dropping the current gain below ten. This allows the thickness of the base to be reduced below 1000Å to improve frequency response while maintaining an acceptable base resistance.

It is beneficial to only slightly dope the emitter 12 in order to reduce the base-emitter capacitance. The higher base doping also distributes the current uniformly throughout the emitter length.

The materials of a collector 16 and the base 10 are generally the same to avoid any heterojunction which can impede the current flow. The material of the collector 16 needs to have a high saturated drift velocity VS and a high breakdown field EC. A high value of the breakdown field allows the thickness of the collector 16 to remain low for a given breakdown voltage. This low thickness, in conjunction with the high drift velocity, minimizes the delay in the collector 16, leading to a higher cut-off frequency and thus improved microwave performance.

In assessing various transistor structures and candidate transistor materials, a figure of merit (FOM) was defined as follows:

$$FOM = P_{out}\, fo^2 \qquad (1)$$

in which P_{out} is power output and fo is the operating frequency. Thus, the unit of the FOM is CV/S^3.

The FOM may equivalently be expressed as follows:

$$FOM = K_G L_{fm} B_{fm} C_{fm} \tag{2}$$

where

$$K_G = K_\theta K_V(0.8) K_f^2 (0.29)^2 q^2 (kT/q)^2$$

letting $K_\theta = 0.1$, $K_V = 0.2$, $K_f = 0.25$ for a particular class of operation (the overall FOM will still be directly proportional for all classes for the product of the individual figures of merit discussed below)

then

$$K_G = 3.47 \times 10^{-43}\ C^2 V^{1/2}$$

L_{fm} is the layout figure of merit (dimensionless) and is defined as:

$$L_{fm} = A_E / L^2 F_C \tag{3}$$

where

A_E is the total emitter area of the layout, L is the size of the single emitter in the length direction of the layout, and F_C is the ratio of the total collector area in the layout to the total emitter area in the layout. For the following comparison, the array of HBTs was constructed such that the layout figure of merit was equal to 176.

B_{fm} is the base figure of merit (in $cm/(V^{1/2} \cdot s^{3/2} \cdot C)$) and is defined as:

$$B_{fm} = (\mu_{nb})^{1/2} \mu_{pb} N_b / \epsilon_s \tag{4}$$

where μ_{nb} is the mobility of electrons in the base, μ_{pb} is the mobility of holes in the base, N_b is the density of p-type acceptors in the base and ϵ_s is the permittivity of the material (8.86×10^{-14} times the dielectric constant).

Finally, C_{fm} is the collector figure of merit (in $V/(cm \cdot s^{3/2})$) defined as:

$$C_{fm} = v_s^{3/2}\ W_C^{3/2}\ N_C\ E_C \tag{5}$$

where W_C is the thickness of the collector, and N_C is the number of dopants in the collector.

Table 1 below illustrates B_{fm} for various candidate base materials.

Table 1. Base FOM

Base Material	K	$\mu_n(cm^2/vs)$	$\mu_p(cm^2/vs)$	$B_{fm}(npn)$ $\left[\frac{cm}{V^{1/2}S^{3/2}C}\right]$	$\frac{B_{fm}}{B_{fm}(GaAs)}$
Ge	16.0	950	110	2.39×10^{34}	1.33
Si	11.9	105	75	0.73×10^{34}	0.40
GaAs	13.1	1200	60	1.79×10^{34}	1.00
GaInAs	13.77	1500	100	3.17×10^{34}	1.77
InP	12.35	1000	30	0.87×10^{34}	0.49
InAs	14.55	2800	90	3.69×10^{34}	2.06
GaN	9.5	100	40	0.48×10^{34}	0.27
3C-SiC	10.0	100	40	0.45×10^{34}	0.25
4H-SiC	10.0	100	40	0.45×10^{34}	0.25

It is evident that GaN and SiC are inferior base materials because of low electron and hole mobilities. However, the choice of the base material is not totally arbitrary and should not be considered in isolation because its characteristics will also depend upon those of the underlying collector material. A heterojunction between the base and collector is not desirable because it can impede the flow of carriers. Thus, the collector figure of merit also must be considered, as shown in Table 2 below.

Table 2. Collector FOM

Collector Material	V_s(cm/s)	E_C(v/cm)	$C_{fm}\left(\frac{v}{cm\ s^{3/2}}\right)$	BV_{CBO} (ideal) $= W_c E_c$	$\frac{Cfm}{Cfm\ (GaAs)}$
Si	0.86×10^7	0.41×10^6	2.07×10^{26}	41.00 V	0.92
GaAs	0.83×10^7	0.47×10^6	2.25×10^{26}	47.00	1.00
InP	1.1×10^7	0.43×10^6	3.14×10^{26}	43.00	1.40
4H-SiC	2.0×10^7	2.00×10^6	35.78×10^{26}	200.00	15.90
GaN	2.5×10^7	3.50×10^6	87.50×10^{26}	350.00	38.89
Diamond	2.0×10^7	5.5×10^6	98.39×10^{26}	550.00	43.73

The overall FOM for various HBT structures is shown in the table in Figure 2. Therefore, the HBT systems of interest are AlGaN/4H-SiC/4H-SiC and AlGan/GaN/GaN, especially on a SiC substrate as shown in the table of Figure 2. AlGaN allows more flexibility in creating band gap differences in controlling junction characteristics. Diamond, also shown in this table, is impractical to fabricate.

The HBT shown in Fig. 1a, includes a base 10 including a layer 24; an emitter 12, including layers 26, 28; a collector 16 including a layer 22; a buffer layer 20; a substrate 18; a collector contact 30; a base contact 32; and an emitter contact 34. The buffer layer 20 serves to improve the breakdown voltage of the base-collector junction. The double base contact 32 reduces the base resistance which is important for superior microwave performance.

Preferably, the base 10 is made of SiC, the emitter 12 is made of AlGaN and the collector 16 is made of SiC. In one preferred embodiment, the substrate 18 is N+ 4H or 6H SiC, the buffer layer 20 is N- 4H or 6H SiC, the collector layer 22 is N 4H or 6H SiC, the base layer 24 is P+ 4H or 6H SiC, the

emitter layer 26 is N AlGaN (hexagonal), and the emitter layer 28 is N+ AlGaN (hexagonal). The layers are formed in a conventional manner. The contacts 30, 32, and 34 are all of conventional contact material. When the buffer layer is 6H or 4H SiC doped layer, it serves to shield the collector field from the substrate, thus preventing premature breakdown.

Alternatively, in the embodiment shown in Figure 1a, the substrate is N+ 4H or 6H SiC, the buffer layer 20 is N+ 4H or 6H SiC, the collector layer 22 is N 4H or 6H SiC, the base layer 24 is P+ 4H or 6H SiC, the emitter layer 26 is N AlGaN (hexagonal), and the emitter layer 28 is N+ GaN (hexagonal).

A second embodiment of the present invention is shown in Figure 1b, in which the structure shown in Figure 1a includes an additional buffer layer 21. The substrate 18, the collector contact 30, the base contact 32, the emitter contact 34, and the emitter layers 26, 28 may be either of the alternatives set forth in above in connection with Figure 1a. The additional buffer layer 21 is preferably N+ GaN (hexagonal). In the embodiment shown in Figure 1b, the collector layer 22 is preferably N GaN (hexagonal) and the base layer 24 is preferably P+ GaN (hexagonal).

The use of SiC as the material for the substrate 18 is critical in the embodiments shown in Figures 1a and 1b because SiC has a high thermal conductivity, i.e., three times higher than that of Si and six times higher than that of GaN, conventionally used for substrates. Thus, the use of a SiC substrate allows more heat to be removed from the device and thus more RF power can be output.

A third embodiment of the present invention is shown in Figure 1c, in which any of the above structures described in connection with Figure 1a and 1b, with or without the buffer layer 21, are mounted

on a semi-insulating substrate 36 of 4H or 6H SiC. This embodiment retains some of the heat removal of SiC layer 18, while the use of a semi-insulating SiC substrate minimizes parasitics, thus enhancing the microwave performance of the HBT.

A fourth embodiment of the present invention is shown in Figure 1d, in which the structures described above in connection with Figure 1b are mounted on the substrate 36 and having a buffer layer 38 between the collector layer 18 and the substrate 36. Preferably, the substrate 36 is sapphire and the buffer layer 38 is semi-insulating, undoped AlN (hexagonal). Sapphire does not provide the heat conducting advantages of SiC, but the large area of the substrate 36 makes the HBT easier to fabricate and lowers the cost of the device, while sacrificing some performance advantage due to not using SiC. Often cost is a major factor, and SiC substrates are very expensive and only exist in 2 inch diameters. Sapphire can be obtained in 5-6 inch diameters. Thus, some applications may desire to forego some high power density, shown in column 1 of Figure 2, for cost and size considerations.

In the structures shown in Figures 1a - 1d, the two-layer AlGaN in the emitter region and the SiC or GaN collector help overcome all the three major limitations described in the background section. The heterostructure created by using an $Al_xGa_{1-x}N$ layer in the emitter provides a higher bandgap region and prevents the injection of holes from the p-type base. This allows the doping in the base region to be raised without degrading the current gain and thus lower the base spreading resistance. The resulting higher base conductivity helps distribute the emitter current more evenly and increases the maximum frequency of operation, f_{max}, for a given cut-off frequency, f_t. The f_t in turn depends primarily on the delay in the collector region which can be made very narrow (<1 μm)

and highly doped ($5x1016/cm^3$) by taking advantage of the high breakdown field of the SiC. The high doping in the collector in combination with high saturated drift velocity of electrons ($2x10^7$cm/sec) increases the collector current per unit of emitter area, thus increasing the power output per unit area and also reducing the delay associated with charging the emitter capacitance. The higher thermal conductivity of the substrate helps remove heat efficiently. The leakage currents associated with electron-hole pair generation ($\propto n_i^2$) are negligible in SiC and GaN up to 400°C due to the higher bandgap of SiC and GaN.

Thus, the transistor of the present invention is capable of operating at high junction temperatures. This transistor is capable of providing 10 W/mm of RF power at 10GHz and at room temperature, which is more than twice the power as the 3-4 W/mm the existing AlGaAs/GaAs HBT technology provides. This transistor may now be used to construct systems having higher power densities, lower chip area, reduced cooling requirements, and reduced weight.

The invention being thus described, it will be obvious that the same may be varied in many ways. Such variations are not to be regarded as a departure from the spirit and scope of the invention, and all such modifications as would be obvious to one skilled in the art are intended to be included within the scope of the following claims.

What is claimed is

1. A heterojunction bipolar transistor comprising:

a collector region;

a base region overlying at least part of said collector region; and

an emitter region including an AlGaN layer overlying at least part of said base region, forming a heterojunction between said base region and said emitter region.

2. The heterojunction bipolar transistor as recited in claim 1, wherein said emitter region comprises two layers.

3. The heterojunction bipolar transistor as recited in claim 2, wherein said emitter region comprises an N- AlGaN layer and an N+ AlGaN layer overlying said N- AlGaN layer.

4. The heterojunction bipolar transistor as recited in claim 1, further comprising a SiC substrate on which said collector layer is mounted.

5. The heterojunction bipolar transistor as recited in claim 4, further comprising a buffer layer between said SiC substrate and said collector region.

6. The heterojunction bipolar transistor as recited in claim 1, further comprising a sapphire substrate on which said collector region is mounted.

7. The heterojunction bipolar transistor as recited in claim 1, further comprising a buffer layer between said sapphire substrate and said collector region.

8. The heterojunction bipolar transistor as recited in claim 1, further comprising a semi-insulating SiC substrate on which said collector layer is mounted.

9. The heterojunction bipolar transistor according to claim 1, wherein said base region comprises a P+ 4H-SiC layer.

10. The heterojunction bipolar transistor according to claim 1, wherein said collector region comprises a N 4H-SiC layer.

11. The heterojunction bipolar transistor according to claim 1, wherein said emitter region comprises an N AlGaN layer and an N+ GaN layer overlying said N AlGaN layer.

12. The heterojunction bipolar transistor according to claim 11, wherein said base region comprises a P+ GaN layer.

13. The heterojunction bipolar transistor according to claim 1, wherein said collector region comprises an N GaN layer.

14. The heterojunction bipolar transistor according to claim 1, wherein said transistor operates in a microwave region.

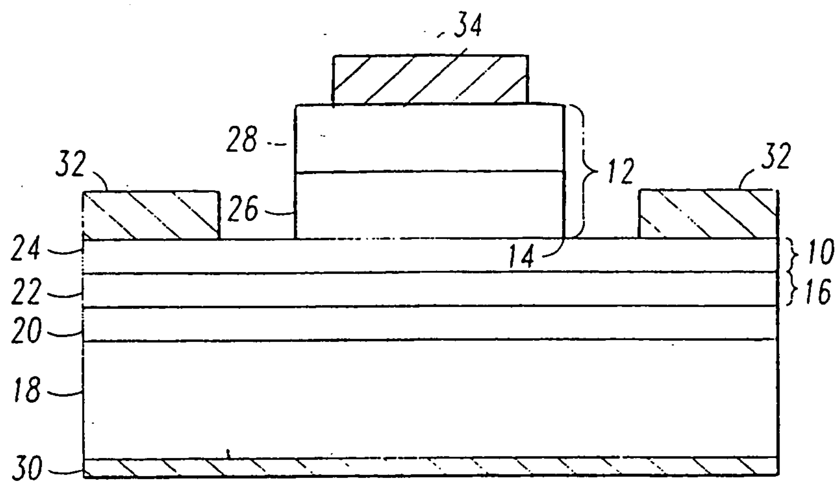
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FIG. 1A

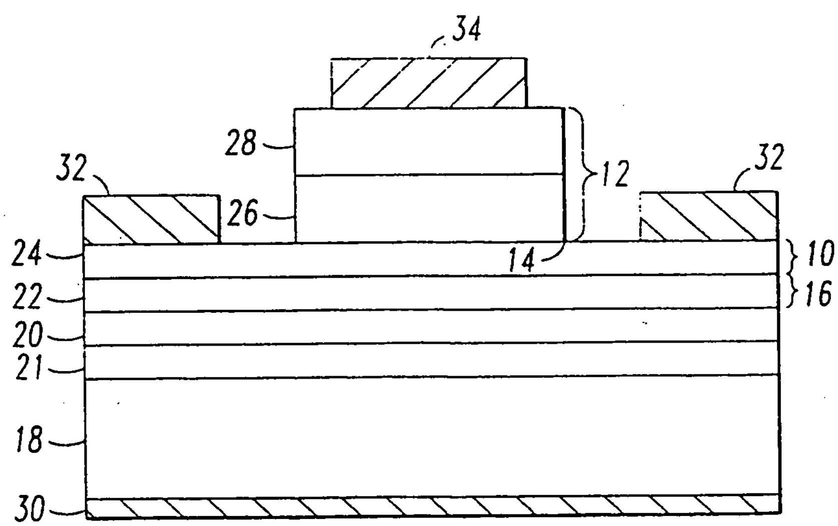
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FIG. 1B

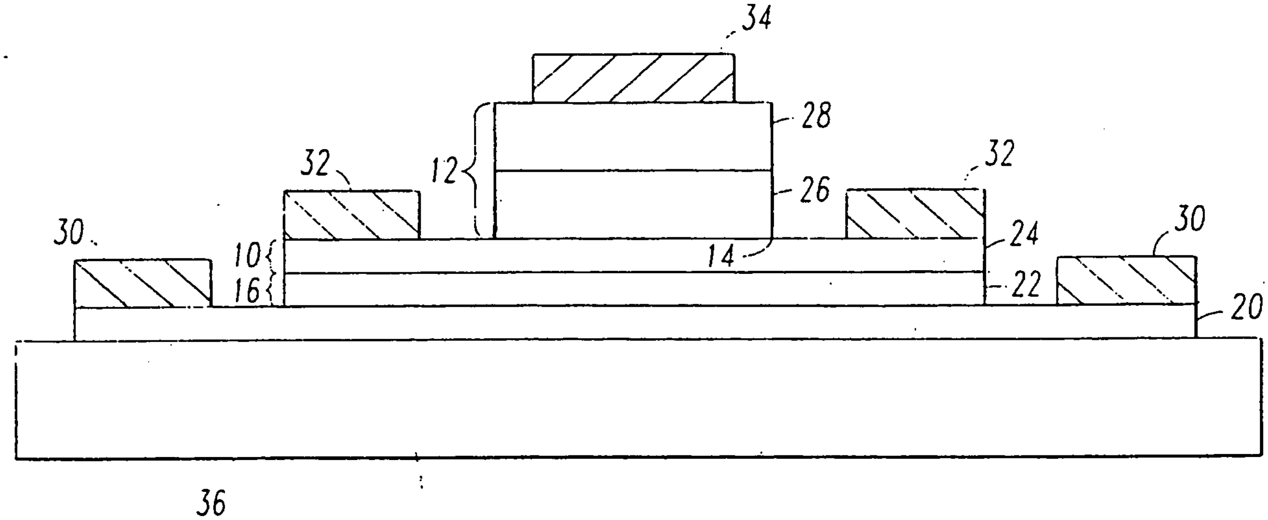
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FIG.1C

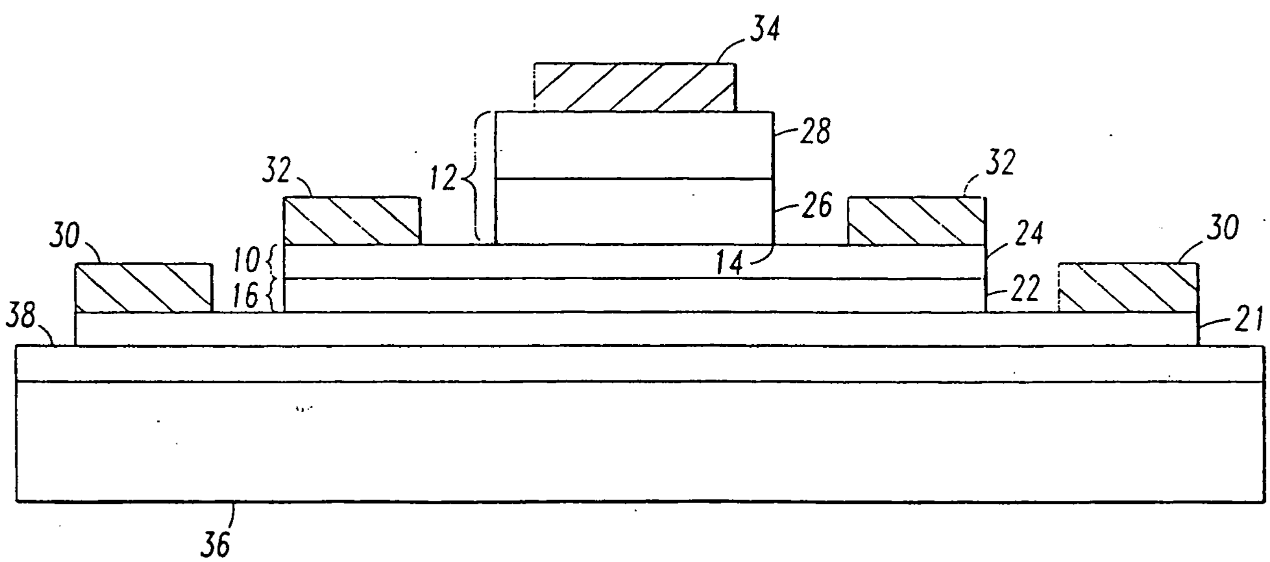
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FIG.1D

Pout W/mm at $f_{max}(opt)/4$	HBT STRUCTURE E/B/C	B_{fm} $\left(\frac{cm}{v^{1/2} s^{3/2} c}\right)$	C_{fm} $\left(\frac{v}{cm\ s^{3/2}}\right)$	f_T (OPT) (GHz)	f_{max} (OPT) (GHz)	FOM $\left(\frac{cv}{s3}\right)$	$\frac{FOM}{(FOM)\ \frac{AlGaAs}{GaAs}}$
0.36 W	POLY-Si/SiGe/Si	0.73×10^{34}	2.07×10^{26}	10.95	63.94	0.92×10^{20}	0.37
0.40	AlGaAs/GaAs/GaAs	1.79×10^{34}	2.25×10^{26}	10.57	99.40	2.46×10^{20}	1.00
0.48	InP/InGaAs/InP	3.17×10^{34}	3.14×10^{26}	14.01	141.67	6.08×10^{20}	2.47
4.10	6H-SiC/3C-SiC/4H-SiC	0.45×10^{34}	35.78×10^{26}	25.48	62.00	9.83×10^{20}	4.00
4.10	AlGaN/4H-SiC/4H-SiC	0.45×10^{34}	35.78×10^{26}	25.48	62.00	9.83×10^{20}	4.00
8.96	AlGaN/GaN/GaN/4H-SiC	0.48×10^{34}	87.50×10^{26}	31.85	67.70	25.65×10^{20}	10.43
11.26	SiC/Si/DIAMOND	0.73×10^{34}	98.39×10^{26}	25.48	78.56	43.86×10^{20}	17.83

FIG. 2

INTERNATIONAL SEARCH REPORT

International Application No
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A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01L29/737 H01L29/267

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H01L

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
E	US 5 641 975 A (AGARWAL ANANT K ET AL) 24 June 1997 see the whole document ---	1-14
X	MOHAMMAD S N ET AL: "EMERGING GALLIUM NITRIDE BASED DEVICES" PROCEEDINGS OF THE IEEE, vol. 83, no. 10, pages 1306-1355, XP000545665 see page 1328 see page 1332; figures 1,30,40,42 ---	1-14
X	PATENT ABSTRACTS OF JAPAN vol. 015, no. 161 (E-1060), 23 April 1991 -& JP 03 034549 A (TOSHIBA CORP), 14 February 1991, see abstract --- -/--	1

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Date of the actual completion of the international search	Date of mailing of the international search report
14 October 1997	12 -11- 1997
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Eliasson, G

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International Application No
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Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5641975 A	24-06-97	NONE	

Form PCT/ISA/210 (patent family annex) (July 1992)

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C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	PANKOVE J ET AL: "HIGH-TEMPERATURE GAN/SIC HETEROJUNCTION BIPOLAR TRANSISTOR WITH HIGH GAIN" 1995 IEEE INTERNATIONAL CONFERENCE ON SYSTEMS, MAN AND CYBERNETICS, VANCOUVER, OCT. 22 - 25, 1995, vol. 1, 22 October 1995, INSTITUTE OF ELECTRICAL AND ELECTRONICS ENGINEERS, pages 389-392, XP000585516 cited in the application see the whole document ---	1
A	CASADY J B ET AL: "Status of silicon carbide (SiC) as a wide-bandgap semiconductor for high-temperature applications: a review" SOLID STATE ELECTRONICS, vol. 39, no. 10, page 1409-1422 XP004012151 see page 1411; table 1 ---	9,10
A	BARKER D ET AL: "EXTREMELY HIGH PEAK SPECIFIC TRANSCONDUCTANCE ALGAAS/GAAS HETEROJUNCTION BIPOLAR TRANSISTORS" IEEE ELECTRON DEVICE LETTERS, vol. 10, no. 7, pages 313-315, XP000035237 see figure 1 -----	2,3,11

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